NASA TECHNICAL MEMORANDUM

NASA TM X-71883

NASA TM X-71883

(NASA-TM-X-71883) A NEW APPROACH TO THE PULSED THERMOCOUPLE FOR HIGH GAS TEMPERATURE MEASUREMENTS (NASA) 13 p HC $3.50 CSCL 14B

N76-18408

Unclas

G3/35 18505

A NEW APPROACH TO THE PULSED THERMOCOUPLE FOR HIGH GAS TEMPERATURE MEASUREMENTS

by George E. Glawe, Herbert A. Will and Lloyd N. Krause
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at the 22nd International
Instrumentation Symposium sponsored by the
Instrument Society of America
San Diego, California, May 25-27, 1976

E-8656

A NEW APPROACH TO THE PULSED THERMOCOUPLE FOR HIGH GAS TEMPERATURE MEASUREMENTS

by George E. Glawe, Herbert A. Will, and Lloyd N. Krause
NASA-Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Pulsed thermocouple systems can be used to measure gas temperatures above the melting point of the thermocouple by various techniques of short term or intermittent exposure of the thermocouple operating at lower temperatures. This paper describes an approach which uses a thermocouple cooled by a small jet of inert gas. When a measurement is to be made, the cooling jet is turned off and the thermocouple allowed to heat up to near its melting point, at which time the cooling is reapplied. The final temperature which the thermocouple should have attained is then calculated by extrapolating an exponential curve fit to the data. Temperature measurements can be recorded and displayed in near real time by using modern high-speed computing systems to perform these calculations. Examples of the technique applied to high temperature jet engine combustor development are presented.

INTRODUCTION

A recent investigation(1) dealing with a search for a suitable noble-metal thermocouple to be used in high-temperature (>1900 K) high-pressure ($>20\text{x}10^5 \text{N/m}^2$, >20 atm) jet engine research combustors showed that the Iridium leg of an Ir-40 Rh/Ir thermocouple is destroyed by oxidation within several minutes. In conjunction with the search for possible thermocouple protective coatings and new thermocouple materials, a program was also initiated to extend the temperature range of existing noble-metal thermocouples by the pulse technique. Various investigators(2-6) have developed systems to utilize pulse thermocouple techniques allowing an inferential measurement of a gas temperature which is higher than the melting points of the thermocouple materials used in the system. The system under study uses a jet of inert gas to cool the thermocouple several hundred degrees below its melting point. When a measurement is to be made, the cooling jet is turned off and the thermocouple allowed to heat up to near its melting point, at which time the cooling is reapplied. The final temperature which the thermocouple should have attained is then calculated by extrapolation using modern high-speed computing systems. It should also be noted that a secondary application of the present probe design with its cooling system can also be utilized. This secondary mode is for the case where the thermocouple materials are capable of operating at the final temperature, but must be cooled to protect them from oxidation when a measurement is not taken. In this type of application, the computing portion of the system under study need not be used. This present report describes the probe design, computing techniques, and test and application results.

THEORY

Assume a thermocouple in a hot gas stream is subjected to a step increase in temperature. The temperature of the thermocouple will increase exponentially. The temperature of the thermocouple, in the absence of radiation and conduction, can be represented by the following well known equation;

$$\frac{T - T_0}{T_F - T_0} = 1 - e^{-t/\tau} \tag{1}$$

where T is temperature, with subscript 0 as initial temperature and subscript F as final temperature, τ is the time constant, and t is the time in seconds. Then letting $A_I = T_F$ and $A_c = (T_F - T_0)$, equation (1) can be rewritten:

$$T = A_I - A_c e^{-t/\tau} \tag{2}$$

The problem is to calculate the value of A_I when it cannot be directly measured (i.e., by letting $t \to \infty$). The calculation technique used is to linearize equation (2) and perform a least squares best fit.(7)

Equation (2) can be linearized by letting

$$M \equiv -1/\tau \tag{3}$$

$$B \equiv \ln(A_c) \tag{4}$$

$$Y \equiv \ln(A_I - T) \tag{5}$$

$$X \equiv t\cdot \tag{6}$$

Then equation (2) can be rewritten in the form of the linear equation

$$Y = MX + B \tag{7}$$

If values for Y can be measured at various values of X, then the values of M and B can be computed using linear regression analysis. The best fit is determined by minimizing the sum of the squares of the deviations of the data points from the line. However, since the value of A_I is unknown, the value of Y cannot be determined directly. Therefore, in order to determine the best value of A_I for a given set of data, the variation of a correlation coefficient with respect to A_I is calculated with $Y > 0$ as a constraint. The best A_I value is the one that maximizes the correlation coefficient.

The correlation coefficient, which is used in minimizing the sum of the squares of the deviations of the data points from the line, is given by

$$r = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{\sqrt{\left[n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2\right]\left[n\sum_{i=1}^{n} Y_i^2 - \left(\sum_{i=1}^{n} Y_i\right)^2\right]}} \tag{8}$$

where $Y_i > 0$ for all i and n = number of data points taken along the thermocouple's exponential heating curve. The value of r will be in the range $-1 \leq r \leq +1$ where the sign corresponds to the sign of the slope M. If $r = 0$ there is no correlation and if $r = \pm 1$ there is a perfect fit with the data.

The corresponding least squares approximation equations for M and B are:

$$M = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2} \tag{9}$$

and

$$B = \frac{\sum_{i=1}^{n} Y_i - M\sum_{i=1}^{n} X_i}{n} \tag{10}$$

COMPUTER PROGRAM

The computer program was set up to determine the value of A_I in equation (1). The procedure for determining A_I is to initially guess at A_I and then increase the guess by some increment until the correlation coefficient r goes through a maximum.

The data which are to be curve fit to the exponential curve consists of a series of temperature readings right after the temperature step is applied. These readings are taken only a fraction of the way up the exponential. The initial guess for A_I is computed by determining the maximum value (T_{max}) of the temperature data point used in the curve fit. Then the initial guess for A_I is

$$A_{IG} = T_{max} + 2.0 \tag{11}$$

where 2.0 was arbitrarily chosen to satisfy the condition $Y > 0$. Once the initial value of A_I has been determined the value of the correlation coefficient can be determined from equation (8).

These calculations have been programmed in Fortran on a digital computer. The flow diagram for the computer program is shown in figure 1. Initially three values of r are calculated corresponding to:

$$A_I = A_{IG} \tag{12}$$

$$A_I = A_{IG} + STEP \tag{13}$$

and

$$A_I = A_{IG} + 2\ (STEP) \tag{14}$$

where initially STEP = 1000. The values of r are tested to determine if r has gone through a maximum. If not, all three values of A_I are increased by the step value ($A_{IG} = A_{IG} + STEP$) and the process repeated. If a maximum has occurred between the three values of r the steps of 1000 are reduced to 100 and the process repeated. The convergence is complete when the step equals one and the maximum value of r is between the three calculated values. The final temperature is then;

$$T_{final} = A_{IG} + STEP. \tag{15}$$

The computer program for calculating T_{final} is shown in table 1. The variables SMX, SMY, SMXY, SMXX, and SMYY are defined as follows;

$$SMX = \sum_{i=1}^{n} X_i$$

$$SMY = \sum_{i=1}^{n} Y_i$$

$$SMXY = \sum_{i=1}^{n} X_i Y_i$$

$$SMXX = \sum_{i=1}^{n} X_i^2$$

$$SMYY = \sum_{i=1}^{n} Y_i^2$$

PROBE DESCRIPTION

A close-up of the head detail of the temperature probe is shown in figure 2 and an overall view of a bench-test set-up is shown in figure 3. A cross-section of the water-cooled probe body is approximately rectangular in shape, 1 cm thick and with a chord depth of 3.3 cm. The thermocouple is a 0.05 cm diameter Pt-13 Rh/Pt wedge shaped configuration 0.75 cm long. Coolant jet tubes are 0.16 cm O.D. by 0.11 cm I.D. tubes slightly projecting from the leading edge of the water-cooled support. Gas coolant flow to each tube is controlled by individual solenoid valves mounted externally on the probe. In this manner, coolant flow is selectively turned off to the individual thermocouple which is to be monitored by the data system.

In order to minimize the delay time of the initial portion of the exponential heating curve, the internal volume of the gas coolant tube between the coolant jet and the solenoid valve is minimized.

TESTS AND RESULTS

Tests were run in a high temperature tunnel[8], a bench-test set-up (fig. 3), and two experimental combustors, through a gas temperature range from 1090 to 1700 K, a Mach number range from 0.05 to 0.35 and at pressure levels from 1×10^5 to 20×10^5 N/m^2. Coolant jet pressure was varied to obtain cooling steps of 80 to 1100 K. In all of these tests the final gas temperature was kept below the melting point of the thermocouple material so that the thermocouple could follow the full heating curve. The previously described computational method was then applied to the initial portion of the curve to derive the final temperature. The calculated final temperature is then compared with the experimentally measured final temperature to determine the curve fit error.

The sections which follow in the TEST AND RESULTS include the following: The effect of variation in coolant jet pressure on the thermocouple indication is described in the section labeled Coolant Jet Effectiveness. Prolonged cycling of the thermocouple is discussed in the section labeled Cycling Tests. Also included in this section are some calculated gas temperature results obtained from analog thermocouple heating curves. (A high speed digitizer was not available in the combustor facility in which the cycling tests were first performed). The Bench Tests section includes thermocouple heating curve results in which the thermocouple output was connected to a minicomputer. And, finally, tests of a prototype of a complete system involving the pulsed thermocouple and computer in an experimental combustor are described in the section labeled Complete System Test In Combustor.

Coolant Jet Effectiveness

Jet pressures of the coolant gas was varied during tunnel and combustor testing to determine the amount of cooling necessary to depress the thermocouple temperature indications to various degrees. The data are presented in figure 4. In these tests the free-stream pressure ranged from 1×10^5 to 20×10^5 N/m^2. The data are plotted in terms of probe coolant pressure in excess of free-stream total pressure versus the cooling effectiveness expressed as a ratio of cooling temperature. The probe coolant pressure was measured just upstream of the solenoid valve. The results presented in figure 4 can be used to estimate the approximate coolant gas supply pressure necessary for a particular application. As an example, figure 4 indicates that with a pressure difference of 6×10^5 N/m^2 the cooled thermocouple would indicate a temperature of about 1000 K in a 2000 K gas stream.

A large step in cooling is advantageous from two points of view. One is that it provides a larger number of data points from which to extrapolate when calculating gas temperatures above the thermocouple melting point. A lower indicated temperature, with the cooling gas applied, also provides more oxidation protection for the thermocouple.

Cycling Tests

Since a pulsed thermocouple is intended to be rapidly heated and cooled through a large temperature range, for many cycles, a cycling test was performed in one of the experimental combustors operating at 20×10^5 N/m^2. The thermocouple was cycled from 755 to 1590 K at a rate of 5 seconds per cycle, for 1 hour. After these 720 cycles, the thermocouple showed no apparent degradation and was, thereafter, subjected to further testing in the program with no failure.

During the cycling tests, analog records were used to acquire data. One such test was made in the combustor at 1600 K and 20×10^5 N/m^2. The heating curves (620 to 1600 K) were repeated six times while combustor conditions were held steady. The resultant curves were analyzed by considering only the initial 60 percent of the heating curve and extrapolating to the final temperature using the computer program. The curve fit error for each data set obtained from the heating curves was then determined. The average of the calculated errors from the six data sets resulted in an error of 1.4 percent in predicting the final gas temperature. The maximum error for a single data set was 5.6 percent.

Bench Tests

The probe was set-up on a laboratory bench and operated with heat input to the thermocouple being provided by a propane torch (fig. 3). Water coolant was supplied to the probe support and laboratory service air supplied the pulse coolant. Jet coolant pressure, solenoid valve cycling time, and flame temperature could be varied. The bench tests were used as a convenient tool to acquire data for developing the curve fitting technique. The probe was connected to a minicomputer to control the gas cooling and to record the thermocouple voltage by using digital sampling.

The bench tests were used to make five separate data sets. These data sets were used to evaluate the previously discussed curve fitting technique. A typical heating curve is shown in figure 5 as the solid line. The data represented by the solid line represent one data set of 1280 sample points. Time between each sample point is 2.5 ms. The computer program was used to curve fit the heating curve of each of five data sets for 20, 40, 60, 80, and 95 percent of the way up the temperature step. The curve represented by ○ and □ in figure 5 is the exponential curve generated by a computer program. The ○ represent the portion of the curve that was curve fit. The □ represent the extrapolated portion of the curve.

Figures 5, 6, and 7 show typical curve fits for 95, 60, and 20 percent of the temperature step. The curve fit error in determining the actual temperature for each percentage of the exponential is shown in table II. In the average error column of table II, the error decreases as larger percentages of the heating curve are used for curve fitting. This is an expected result. For adequate accuracy (i.e., < 3 percent) at least 60 percent of the heating curve should be used for curve fitting. Even for percentages of 60 percent or greater, occasionally errors significantly greater than that for adequate accuracy will occur. Such is the case of the 8 percent error in Data Set 4 of table II. Such errors can result from temperature fluctuations inherent in combustion gas streams which influence the calculated exponential curve. This points out the shortcoming of the pulsed thermocouple technique.

Complete System Test in Combustor

A prototype pulsed thermocouple system was integrated into the running schedule of an experimental combustor program. The jet coolant solenoid valve cycling operation and the thermocouple output were connected to and controlled by the test facility minicomputer. Gaseous nitrogen was used as the jet coolant. The combustor was operated at 5.5×10^5 N/m^2 pressure and the average cooling cycle temperature step was from 1130 K (coolant on) to 1680 K (coolant off). Data were also taken for short periods of time to measure the burner temperature fluctuations at the high end of the cycle (coolant off). Maximum peak to peak differences indicated by the thermocouple were as great as 55 K (with a thermocouple time constant of approximately 70 ms). This measurement was made to get an idea of the degree of fluctuation which would be superimposed on and perturb the heating curve.

A typical heating curve obtained in the combustor is shown in figure 8. The solid line again shows the actual data. The ○ and □ show the calculated curve. Because of the limited speed of the digitizer used in the combustor facility, only six points on the heating curve were available for curve fitting. Two additional data sets were generated from heating curves at the conditions of figure 8. The average of the calculated errors from the three data sets resulted in an error of 2.1 percent in predicting the final gas temperature. The maximum error for a single heating curve was 4.4 percent.

The combustor tests of the prototype pulsed thermocouple system were, by necessity, limited in scope in order to avoid interference with the main goals of the combustor program. The results are favorable even though the number of sets and data points per set were limited.

CONCLUDING REMARKS

The pulsed thermocouple may be applied in situations within the melting point of the thermocouple as well as when the gas stream is beyond the melting point. Cooling the thermocouple affords oxidation protection against environments encountered in high pressure combustors. Protection is also afforded against "hard starts" and shut-downs in which the gas stream temperature may momentarily rise above the thermocouple melting point.

From results presented herein, in order to use the pulsed thermocouple above its melting point data must be obtained on the heating curve for about 60 percent or more of the imposed temperature step in order to obtain adequate accuracy (error less than 3 percent). About a dozen points should be adequate for defining the data set from which the curve fit is calculated. In addition, because of temperature fluctuations encountered in combustion gas streams, the average of several heating curve data sets is required. The exponential curve fitting technique presented herein is designed to decrease the magnitude of the effects of the gas temperature fluctuations superimposed on the thermocouple heating curve. However, even using this technique, some of the experiments indicated that occasionally one set out of repeated sets of data would show a curve fit error much greater than the average of the remaining data sets. These larger errors can occur when the period of temperature fluctuation of the combustor is of the order of the time constant of the pulsed thermocouple, thus, skewing the exponential heating curve to a high degree. A statistical analysis of the variation in curve fit errors for repeated sets of data indicate a very low probability for these occasional large errors, and suggest that they may be treated as "wild" points. In the present investigation such large curve fit errors were not discarded in the averaging and are presented as maximum curve fit errors.

Although no radiation corrections were applied to the heating curves or final thermocouple indications, such corrections are required in actual combustor applications in order to calculate combustor performance. For the case where the gas temperature is above the thermocouple melting point, the radiation correction would vary according to the indicated thermocouple output position on the heating curve.

From the above considerations it is obvious that modern computers and associated techniques are required in order for the pulsed thermocouple to be practical when applied to any fluctuating temperature environment such as a combustor. Furthermore, these computers provide the potential for obtaining real-time temperature measurements when using pulsed thermocouples during combustor testing.

REFERENCES

(1) Glawe, G. E. 1975. "New High-Temperature Nobel-Metal Thermocouple Pairing," Rev. Sci. Instrum. 46 (8): 1107-1108.

(2) Wormser, A. F. and Pfunter, R. A. 1962. Pulse Technique Extends Range of Chromel Alumel to 7000° F." Paper 524A presented at the S.A.E. National Aeronautical Meeting, April.

(3) Geidt, W. H. and Corallo, R. A. 1968. "Determination of High Gas-Stream Temperatures from Short-Exposure Probe Responses," Instru. Soc. Am. Trans. 8 (1): 43-51.

(4) Raezer, S. D. and Olsen, H. L. 1962. Temperature its Measurement and Control in Science and Industry, Vol. III, Pt. 2, pp. 901-906.

(5) Gautrot, D. 1972. "Temperature Probes for Flows at High Enthalpy." Report ONERA TP-1074, Office National D'Etudes De Recherches Aerospatiales, France, pp. 95-99.

(6) Bzhozovski, V., Sukerer, S., and Yendzheyets, S. 1966. "A Dynamic Thermocouple for Measurement of Plasma Temperature to 4000° C." Report FTD-MT-65-528, Foreign Technology Division, Wright-Patterson Air Force Base, Oh.

(7) Chatfield, C. 1970. Statistics for Technology, Penguin Books, LTD., pp. 166-197.

(8) Glawe, G. E., Johnson, R. C., and Krause, L. N. 1962. Temperature its Measurement and Control in Science and Industry, Vol. III, Pt. 2, A. I. Dahl, ed., Reinhold Publ. Corp., pp. 587-593.

TABLE I. - COMPUTER PROGRAM

```
C      SOURCE.CURVFIT
C
       DOUBLE PRECISION NN,SMX,SMY,SMXY,SMXX,SMYY
       DOUBLE PRECISION TMAX,AI,AIG,Y,NUM,DEN,STEP
       DOUBLE PRECISION R(3),B,M,T(100),TIME(100)
       REAL N1
       INTEGER N,I,J,FLAG
C      N1 = NUMBER OF DATA POINTS
C      N = NUMBER OF DATA POINTS
C      NN = NUMBER OF DATA POINTS
 10    READ (6,20) N
 20    FORMAT (I4)
       N1 = FLOAT (N)
       NN = DBLE (N1)
       DO 40 I = 1,N
       READ (6,50) T(I)
 40    READ (6,50) TIME(I)
 50    FORMAT (F9.3)
C
C      DETERMINE TMAX
C
       TMAX = 0.0
       DO 60 I = 1,N
       IF (T(I).GT.TMAX) TMAX = T(I)
 60    CONTINUE
C
       AIG = TMAX+2.0
       STEP = 1000.0
 70    AI = AIG
       IF (AIG.GT.6000.0) GO TO 120
C
       DO 90 J = 1,3
       SMX = 0.0
       SMY = 0.0
       SMXX = 0.0
       SMYY = 0.0
       SMXY = 0.0
C
C      CALCULATE R
C
       DO 80 I = 1,N
       Y = AI-T(I)
       Y = DLOG (Y)
       SMX = SMX+TIME(I)
       SMY = SMY+Y
       SMXY = SMXY+TIME(I)*Y
       SMXX = SMXX+TIME(I)**2.0
 80    SMYY = SMYY+Y**2.0
C      NUM AND DEN ARE DUMMEY VARIABLES
       NUM = NN*SMXY-SMX*SMY
       DEN = (NN*SMXX-SMX**2.0)*(NN*SMYY-SMY**2.0)
       DEN = DSQRT(DEN)
       R(J) = NUM/DEN
       R(J) = DABS (R(J))
 90    AI = AI+STEP
C      FLAG = INTEGER INDEX
       FLAG = -1
       IF (R(1).LE.R(2)) FLAG = FLAG+1
       IF (R(2).LE.R(3)) FLAG = FLAG+1
       IF (FLAG.EQ.1) GO TO 140
       IF (FLAG.EQ.0) GO TO 110
       IF (STEP.NE.1) GO TO 100
       Z = TMAX-2.0
       IF (AI.LE.(TMAX-TZERO)) GO TO 120
 100   STEP = STEP/10.0
       GO TO 70
 110   IF (STEP.NE.1) GO TO 100
       GO TO 150
 120   WRITE (6,130)
 130   FORMAT (18H DOES NOT CONVERGE)
       STOP
 140   AIG = AIG+STEP
       GO TO 70
C
 150   WRITE (6,170) AIG
 170   FORMAT (21H FINAL TEMPERATURE = ,F8.1,6H DEG. )
       STOP
       END
```

TABLE II. - CALCULATED TEMPERATURE ERROR

Percent of exponential	$(T_{calc} - T_{meas})/T_{meas}$, percent					Average error, percent
	Data Set					
	1	2	3	4	5	
20	95	>100	-5.3	>100	21.2	>100
40	7.1	2.5	36.5	5.9	3.8	11.2
60	-0.1	1.8	2.1	8.0	2.6	2.9
80	0.4	4.6	-1.7	3.1	1.8	1.6
95	3.7	1.0	1.2	1.0	0.3	1.5

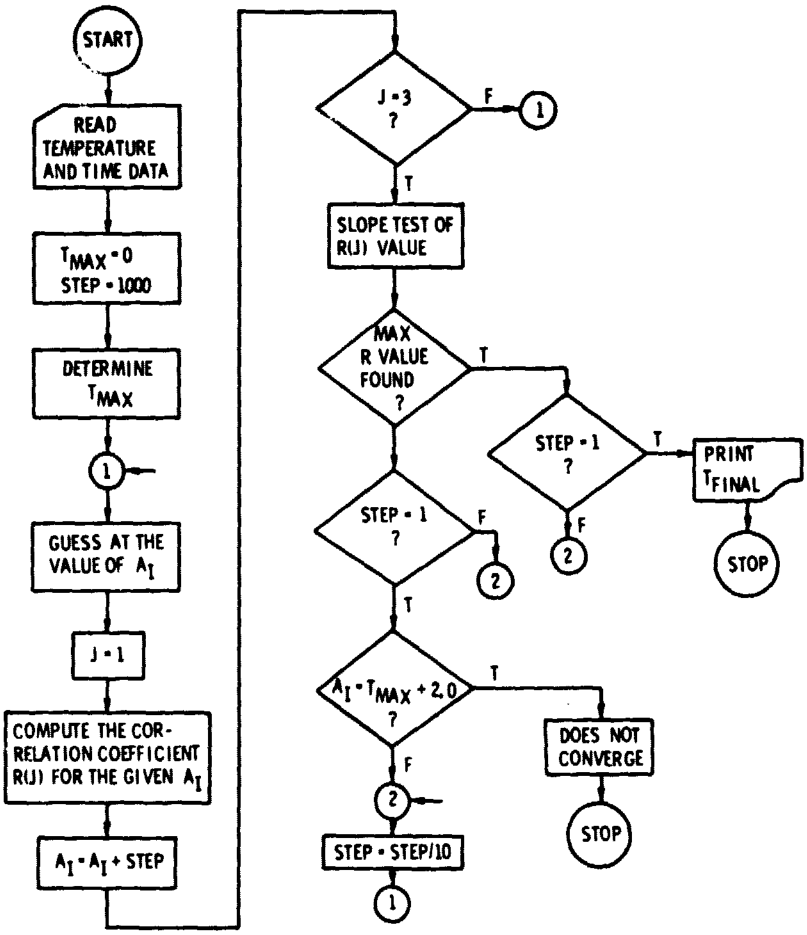

Figure 1. - Flow chart for determining T_{FINAL}.

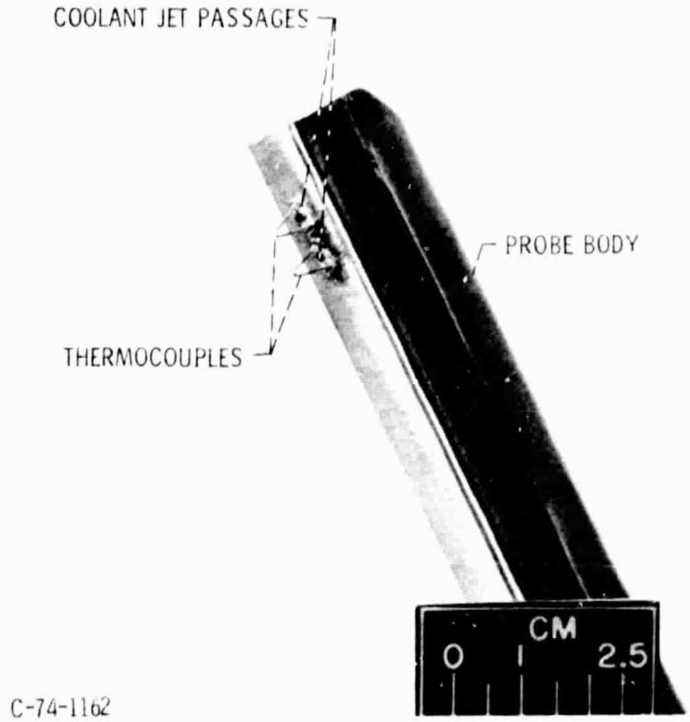

Figure 2. - Pulsed thermocouple probe head detail.

E -8656

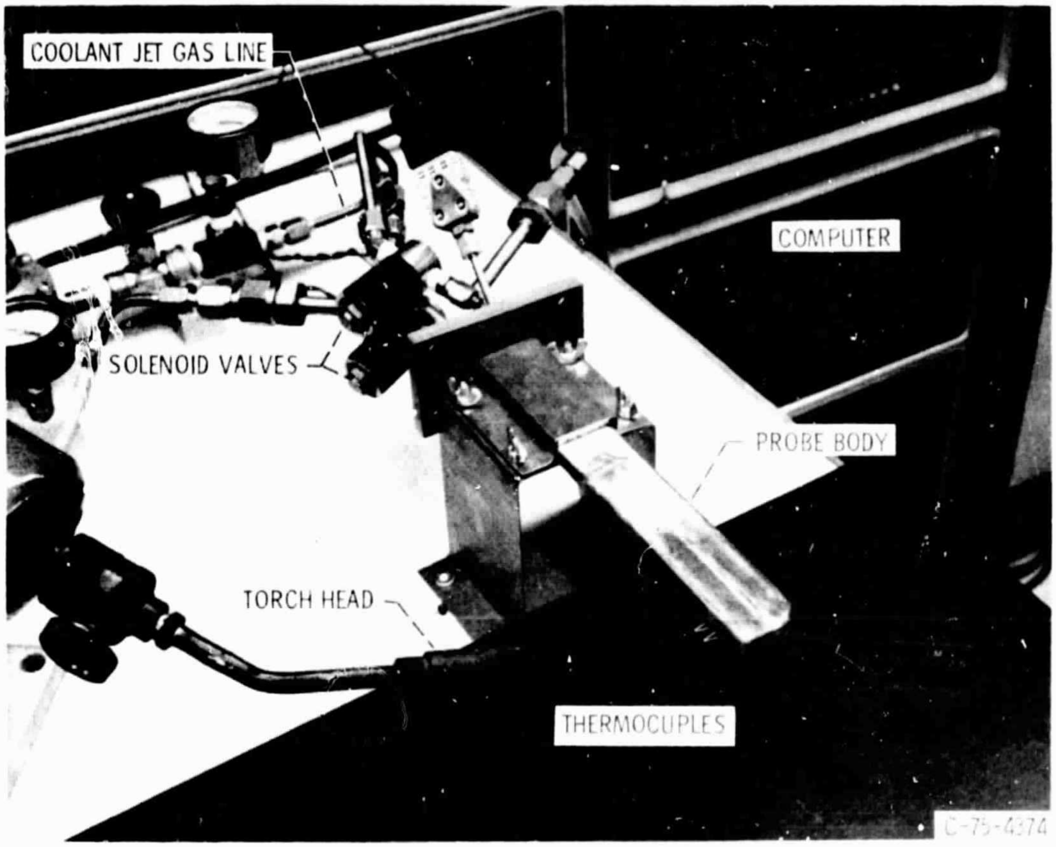

Figure 3. - Laboratory bench test.

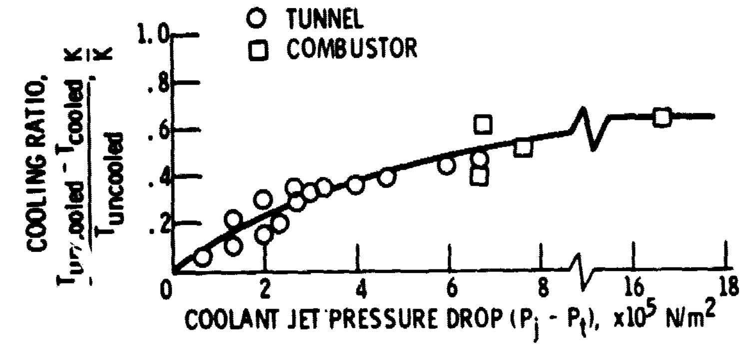

Figure 4. - Coolant jet effectiveness in terms of cooling temperature step ratio and probe coolant jet pressure (P_j) in excess of stream total pressure (P_t).

L-8656

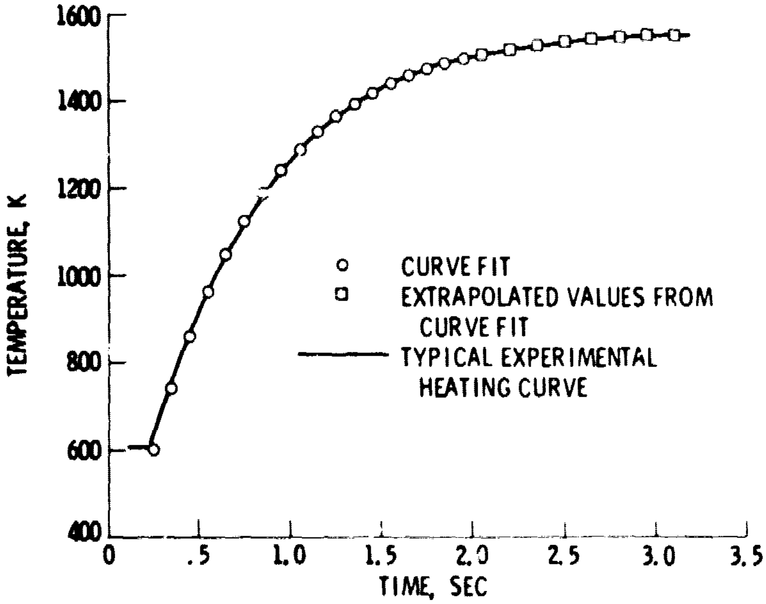

Figure 5. - Comparison between a typical bench test experimental curve to the curve fit for 95 percent of the temperature step.

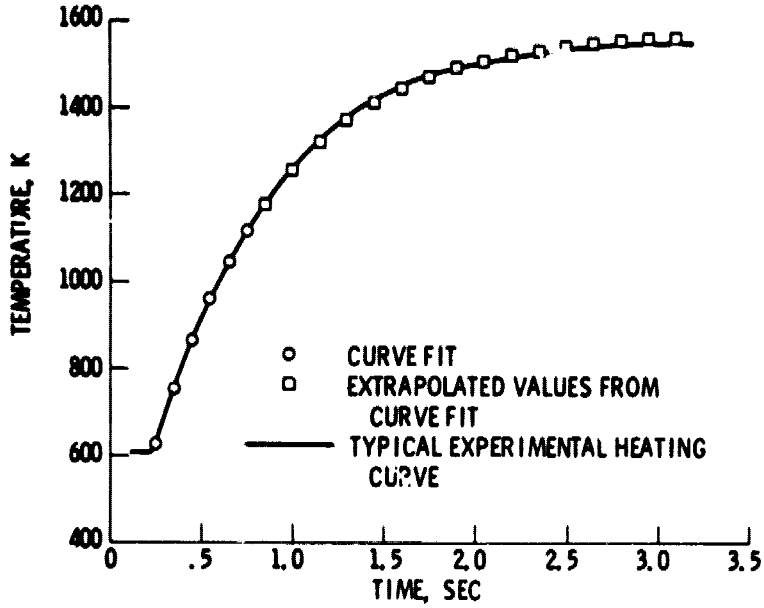

Figure 6. - Comparison between a typical bench test experimental curve to the curve fit for 60 percent of the temperature step.

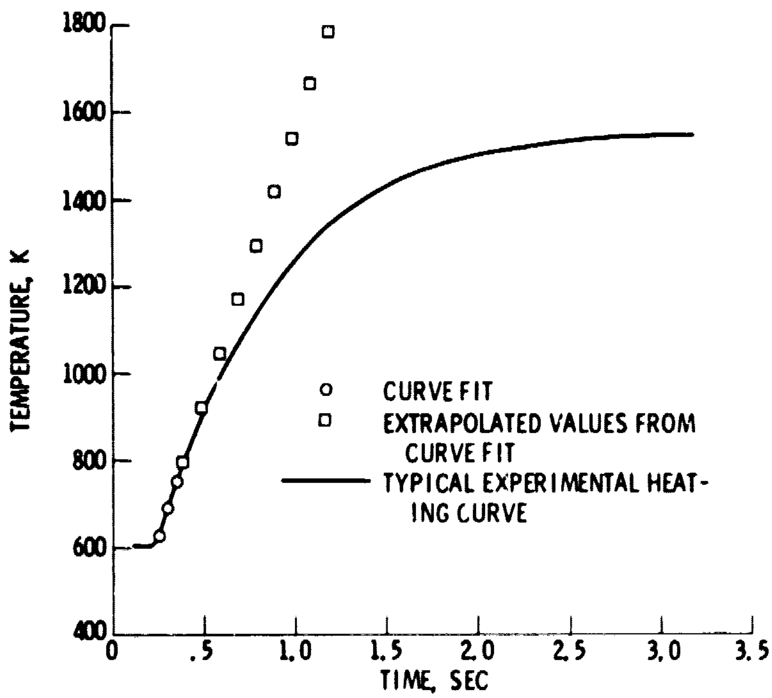

Figure 7. - Comparison between a typical bench test experimental curve to the curve fit for 20 percent of the temperature step.

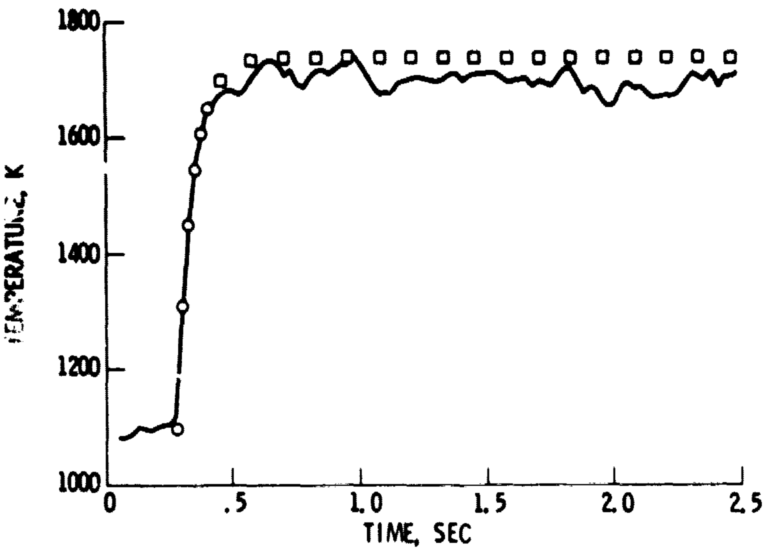

Figure 8. - Curve fit for complete combustor system.

E-8656

NASA-Lewis